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High-Resolution Adaptive Optics Test-Bed for Vision Science

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ABSTRACT

We discuss the design and implementation of a low-cost, high-resolution adaptive optics test-bed for vision research. It is well known that high-order aberrations in the human eye reduce optical resolution and limit visual acuity. However, the effects of aberration-free eyesight on vision are only now beginning to be studied using adaptive optics to sense and correct the aberrations in the eye.[1] We are developing a high-resolution adaptive optics system for this purpose using a Hamamatsu Parallel Aligned Nematic Liquid Crystal Spatial Light Modulator. Phase-wrapping is used to extend the effective stroke of the device, and the wavefront sensing and wavefront correction are done at different wavelengths. Issues associated with these techniques will be discussed.

Keywords: Adaptive optics, liquid crystal, spatial light modulator, vision, ophthalmology, visual acuity.

1. INTRODUCTION

New advances in ophthalmology may enable considerable enhancements in normal vision. Normal human visual acuity is 20/20 on the Snellen scale after correction for the two main sources of aberration in the eye: defocus and astigmatism. However, it has been shown[2] that there are higher-order wavefront error inherent in the lens and cornea with a typical amplitude ~ 0.25 microns rms over a 5.7 mm pupil diameter. Even this seemingly small amount of aberration can dramatically influence the Point Spread Function (PSF) of the eye. In particular, the spatial sampling of the average human retina can support better than 20/10 visual acuity if these higher-order aberrations are corrected. This corresponds to a diffraction-limited image on the retina, where the resolution is limited only by the pupil size, and the photoreceptors (typical diameter ~ 3-5 microns) sample the image 1 to 1. This is basically where the optical resolution matches the retinal resolution. This situation brings up a number of interesting questions relating to the ultimate resolution of human vision, and potential role that physical, physiological, and psychological factors will have on the limitations. At this time, only with adaptive optics can one contemplate initiating a useful study on the effects of supernormal vision, since this is the only way to correct for the large number of high-order aberrations in the eye, and assess the resulting supernormal vision. Several vision science laboratories around the world that have successfully demonstrated the use of adaptive optics in this context.[3, 4,5,6]

2. DESCRIPTION OF TEST-BED

We are developing an adaptive optics system that can be used to sense and correct aberrations in a subject's eye and allow detailed studies of visual performance under a variety of conditions. This work benefits from our expertise in adaptive optics for large lasers and astronomical imaging, particularly in association with the laser guide star program.[7] In addition, we have demonstrated high resolution wavefront control[8] using liquid crystal spatial light modulators (LC-SLM's)[9] made by Hamamatsu. A schematic of the test-bed used to characterize the wavefront correction of the device is shown in Fig. 1. In the context of vision correction, the front end laser (a HeNe operating at 633 nm) represents a laser beacon that would be reflected off the back of the retina, which is a standard method used in sensing the aberrations present in the eye using a Hartmann sensor. A 785 nm laser diode beam can also be injected into the front end. This is nescessary for the two-color experiments discussed below.

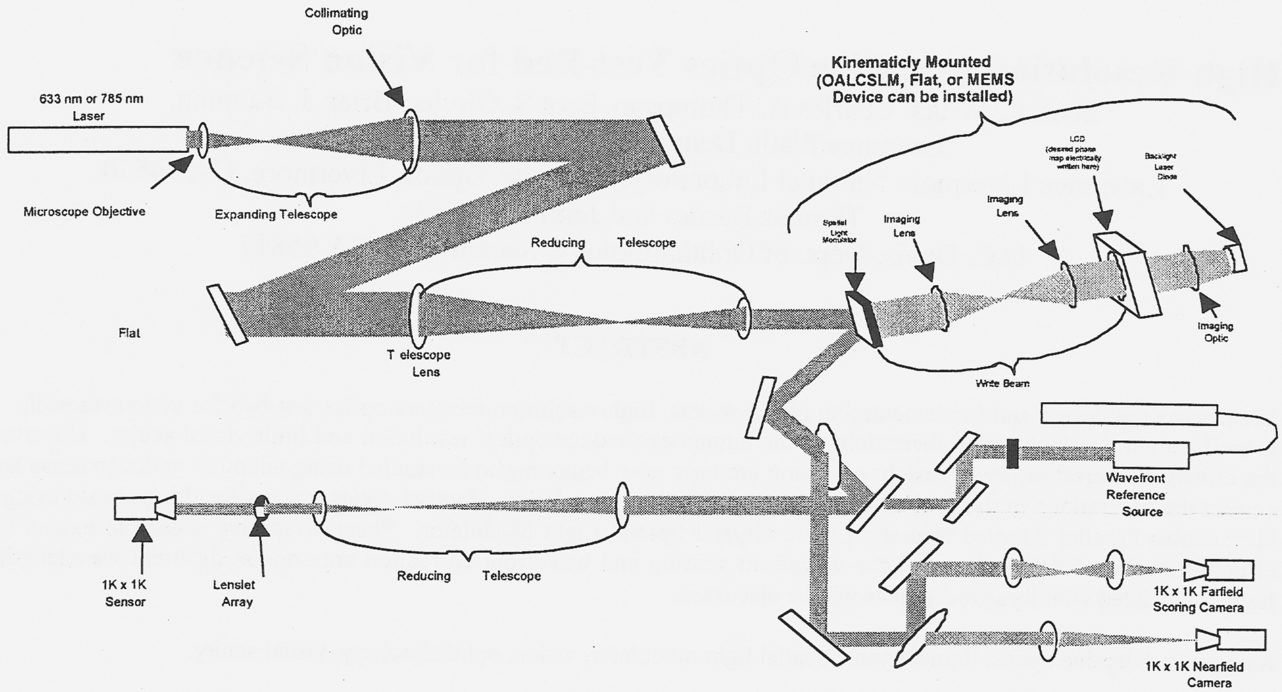

Figure 1: Schematic of the Adaptive Optics test-bed.

Some of the more novel aspects of the wavefront correction device we use will now be discussed. The device is optically addressed by writing a particular pattern onto an LCD inside the device. This step is similar to writing onto a computer screen; the pixel format of the LCD is 640 by 480. Once this pattern is written to the LCD, it is projected onto the back of the SLM, where the intensity of the pattern causes the nematic liquid crystals on the front face to retard the phase to a greater or lesser degree, depending on the corresponding pixel value written to the LCD (a value between 0 and 255.) Aberrated light is then incident onto this front face, and the phase of the wavefront is altered depending on the phase of the front of the device. The actual number of useful pixels on the device are 480 by 480, which corresponds to the reflecting surface of 20 mm x 20 mm on the front of the SLM. Since each pixel can be addressed separately, the effective number of actuators is 230,400. Since the effective stroke of any single actuator is limited to slightly less than one micron, phase wrapping must be employed to increase the effective stroke beyond this range.

A variable frequency generator drives the SLM. By adjusting the voltage, the frequency, and the pattern of the signal (a sinusoidal voltage gave the best results) we found we could maximize the amount of stroke the device can provide. Fig. 2 shows a plot of the stroke versus the voltage, for a number of frequencies. As will be discussed in detail below, we would like the ability to phase wrap at both 785 nm light, as well as 550 nm.. Thus, we needed at least this amount of effective phase change to have one complete wave of stroke. It is interesting to note that the recommended voltage and frequency are 2 volts and 1 kHz, respectively.

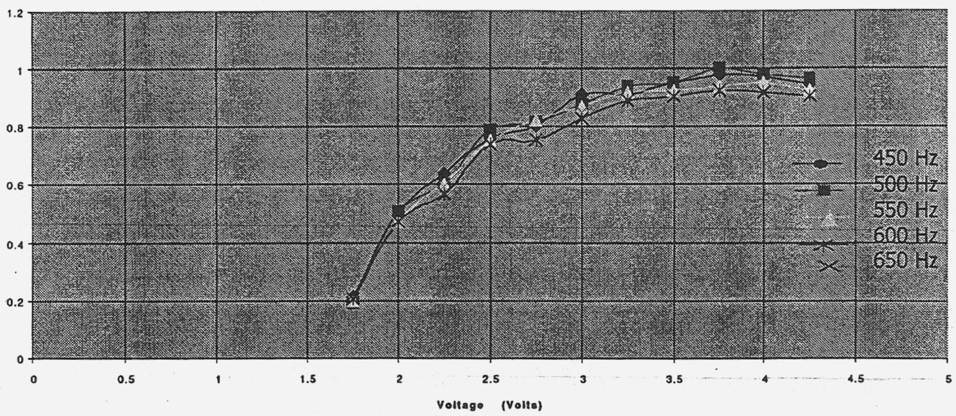

Figure 2: SLM stroke as a function of voltage, for various frequencies between 450 and 650 Hz.

Once the voltage and frequency of the LC-SLM have been chosen, the actual stroke as a function of write pixel value is measured. This is done using a WYKO interferometer at normal incidence, using 633 nm light. By writing images of gaussians (50 pixels FWHM) onto the center portion of the LCD of the SLM, we can measure the effective stroke of the device. This is done by initially setting the peak of the gaussian to a pixel value PV = 255 and measuring the stroke obtained. This procedure is repeated until the peak of the gaussian is reduced to zero, or PV = 0. A plot of the results is shown in Fig. 3. This measurement has been made at several points across the device, and it was found that the response of the device varies

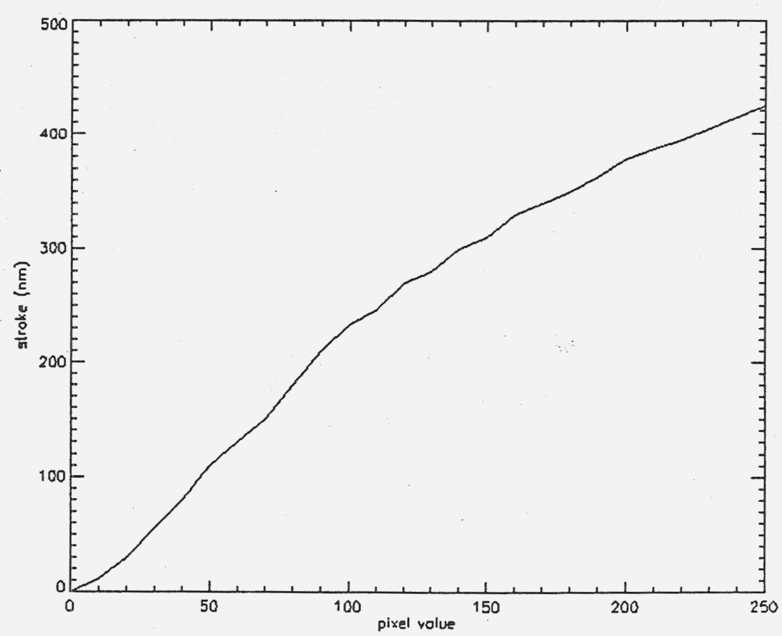

Figure 3: The SLM response at the center of the device. The response varies slightly across the surface of the device.

across the surface. The average response is relatively linear for each region locally, but the slope for each region is slightly different. However, for first order effects, we can assume a roughly equivalent response over the entire surface, realizing that the amount of error increases as the pixel value increases. This error is about 5 nm for stroke values below 200 nm of stroke, increasing linearly to plus or minus 40 nm at peak stroke, which is about 400 nm.

A minor issue is that the optical quality of the SLM is not perfect. The most recent SLM's that we have characterized are reflective over a broad range of wavelengths: about 400 nm to 850 nm. These devices have a non-negligible amount of lower order aberration, even unpowered. As can be seen in Fig. 4, there is approximately 740 nm of wavefront Optical Path Difference (OPD) of aberration present in the device (RMS: 200 nm, Peak to Valley: 737 nm). The device can be self-correcting, in the sense that we can send a signal to the device that will compensate for the aberration, primarily correcting for focus, astigmatism, and coma. We call this a "flat file", in that it flattens out the SLM face such that a perfect wavefront reflected off the surface of the SLM with this pattern written to the LCD on the device, will remain flat to a high degree. This flat file is shown in Fig. 5, and it is clear that we must use the entire stroke of the device to correct the aberrations inherent in this SLM. (Note the SLM flips the image as seen by the WYKO in both the horizontal and vertical planes.) By applying flat files to the LCD of the SLM, we are easily able to correct the aberration to better than 75 nm peak to valley wavefront (13 nm RMS.) In addition, we have also explored using only a small circle of the front of the SLM (an 8 mm diameter circle) where the local unpowered aberration is small. In this case, we obtain about 55 nm of wavefront peak to valley (9 nm RMS.)

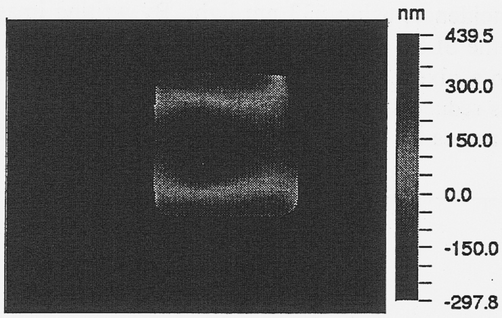

Figure 4: Aberration of the SLM.

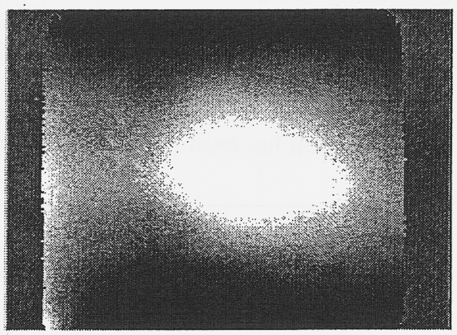

Figure 5: A flat file, 0 < PV < 255.

We are now in a position to contemplate correcting external aberrations, for example, those present in the human eye. It is thought that a maximum stroke of 7 microns would ensure that all but a few extreme cases of human eye aberration could be corrected. In order to achieve this range with this device, we must wrap the phase. The first step in phase wrapping is to determine which wavelength the device will wrap, such that a continuous phase, over several waves, can be mimicked. Both the WYKO and our test bed have a 633 nm HeNe. The second step is to find the pixel value to be sent to the LCD on the SLM, such that an OPD of a 633 nm (a wavelength of the light to be wrapped) will be achieved on the front face of the SLM. Referring to Fig. 3, we see that we can phase wrap if we choose our peak pixel value to be PV = 150, where the surface changes by about 315 nm. In order to check this, we "wrapped" the flat file shown in Fig. 5 at the peak pixel value of PV = 150. This file, along with the resulting WYKO image, is shown in Fig. 6.

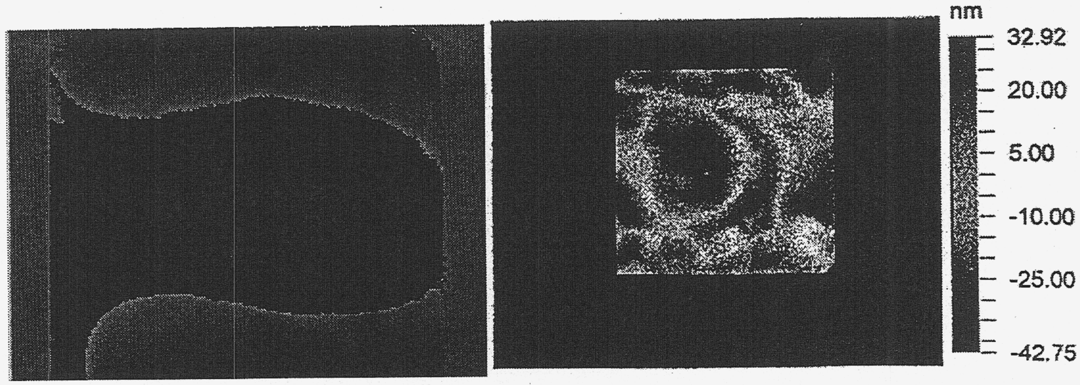

Figure 6: (a) A flat file wrapped at 150. (b) The corresponding WYKO image. This resulted in a peak to valley OPD of 75.6 nm over most of the face.

3. PROTOTYPE ADAPTIVE PHOROPTER

We are currently assembling a prototype phoropter based on the LC-SLM described above to be used for vision science experiments to be conducted at the UC Davis Department of Ophthalmology. A schematic of the system is shown in Fig. 7. Briefly described, this instrument will shine low level collimated laser light (< 10 µWatts) at 785 nm into the eye of a human subject, which will focus onto the retina. Some small fraction of this light will then reflect off the retina, serving as a "beacon" for sensing the aberrations present in the eye (most of which reside in the lens and the cornea.) The light from this beacon will then be reflected off the SLM, and sent to a 20 x 20 lenslet array that will allow us to determine the slopes of the wavefront, having been aberrated by the eye. We then use this information to construct signals to be sent to the LC_SLM such that we exactly compensate for those aberrations. Simultaneously, the subject will be looking through the system, off the face of the SLM, to a computer monitor that is showing

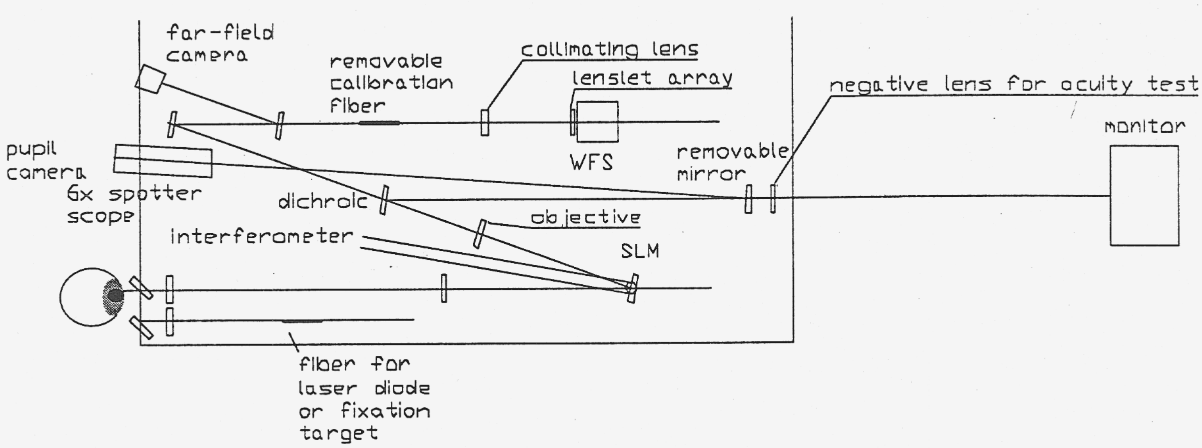

Figure 7: Optical layout of a vision science system currently being assembled at LLNL.

images in black, on a monochromatic green light (550 nm) background. By sensing the light reflected from the back of the retina, we can control the surface of the SLM such that enhanced vision via a closed loop control will result. Many vision science tests are planned to study visual acuity using this particular set up.

There are many benefits to using an SLM for vision correction. Due to the extremely high number of effective actuators (480 x 480 = 230,400) the accuracy of correction can potentially be quite high. In particular, this is useful for phase

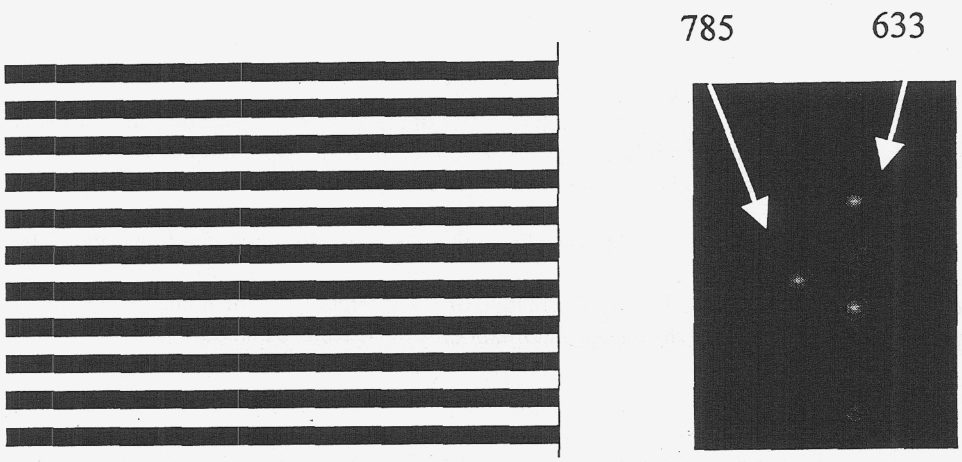

Figure 9: (a) Bar pattern written to the LCD of the SLM, with peak PV = 254. (b) Far field spot observed for both colors simultaneously in the system.

CONCLUSION

In conclusion, we have described a novel optical device, based on a LC-SLM, which will be capable of studying the limits of visual acuity. A number of tests have been conducted and described prior to the design and building of the device, and it has been determined that this LC-SLM has many desirable features for correcting high order aberrations. Specifically, the near-one micron of stroke, and the large number of actuators (480 x480) make for potentially high accuracy phase wrapping. Two of us (TB and JSW) would like to acknowledge funding from the National Institute on Aging (AG04058 and Research to Prevent Blindness.

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